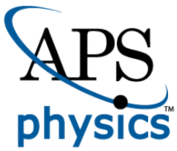

Top-Quark Mass Measurement Using Events with Missing Transverse Energy and Jets at CDF

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Top-quark mass measurement using events with missing transverse energy and jets at CDF

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We present a measurement of the top-quark mass using a sample of $t\bar{t}$ events in 5.7 fb^{-1} of integrated luminosity from $p\bar{p}$ collisions at the Fermilab Tevatron with $\sqrt{s} = 1.96$ TeV and collected by the CDF II Detector. We select events having large missing transverse energy, and four, five, or six jets with at least one jet tagged as coming from a b quark, and reject events with identified charged leptons. This analysis considers events from the semileptonic $t\bar{t}$ decay channel, including events that contain tau leptons. The measurement is based on a multidimensional template method. We fit the data to signal templates of varying top-quark masses and background templates, and measure a top-quark mass of $M_{top} = 172.3 \pm 2.4$ (stat) ± 1.0 (syst) GeV/c^2.

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The top quark (t) is the heaviest known elementary

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particle, with a mass approximately 40 times heavier than the mass of the bottom quark (b), its partner in the weak isospin doublet. The top-quark mass can be used as a consistency check for standard model (SM) parameters. For example, the top quark contributes significantly to electroweak radiative corrections relating the mass of the top quark, M_{top}, and that of the W boson to the mass of the predicted Higgs boson within the SM and in new physics models [1, 2]. Therefore, combined precision measurements of the W mass and M_{top} provide an important constraint on the Higgs boson mass. At the Tevatron, the top quark is predominantly produced in $t\bar{t}$ pairs. As in the SM the top quark decays almost exclusively to a W boson and a b quark, the expected signature of a $t\bar{t}$ production event is $t\bar{t} \to W^+bW^-\bar{b}$, assuming unitarity of the three-generation CKM matrix [3]. Since the W boson subsequently decays either to a quark-antiquark pair or to a lepton-neutrino pair, the final state of $t\bar{t}$ production can be classified by the number of charged leptons produced. In this letter, we focus on events with large missing transverse energy ($\not\!\!E_T$) [4] as expected for undetected energetic neutrinos, accompanied by jets. We explicitly veto events with identified high p_T electrons or muons (lepton+jets events) as well as multijet events where both W bosons decay hadronically (all-hadronic events). This ensures that our result is statistically independent from other CDF top-quark mass measurements [5–8] and allows for a future combination with them. A previous measurement of M_{top} in this final state used an integrated luminosity of 311 pb^{-1} [9] and yielded $M_{top} = 172.3 \pm 15.3$ (stat) ± 14.4 (syst) GeV/c^2. Although no identified leptons are explicitly required, our measurement is sensitive to all W leptonic decays. This includes decays to τ leptons, which constitute approximately 40% of the signal sample in our final selection. The frequency of observed τ lepton final states is predicted to be enhanced by new physics models such as a charged Higgs decay [10], therefore, a significantly different measurement of M_{top} in this decay channel could indicate contributions from non-SM [11] physics processes.

We use data corresponding to an integrated luminosity of 5.7 fb^{-1} of $p\bar{p}$ collisions at the Fermilab Tevatron, and collected by the CDF II Detector [12]. The sample of events used in this measurement is a subset of events that initially passed a trigger requirement, which accepted events with at least four calorimetric clusters [13] of $E_T > 15$ GeV and a scalar sum E_T of these clusters greater than 175 GeV [14]. After the trigger selection, event observables of physical interest are computed. Jets are reconstructed with the JETCLU [15] algorithm using a cone radius of $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$ [16]. Jets are corrected [17] for nonuniformities of the calorimeter response as a function of η, energy contributed by multiple $p\bar{p}$ interactions in the event, and calorimeter nonlinear response. To determine if a jet originated from a b quark, a secondary vertex algorithm [18] is applied. This algorithm identifies jets that are likely to come from b quark hadronization through the presence of a displaced vertex within the jets (b-tag). We require at least one jet to be identified as a b jet (b-tagged). We divide the sample of candidate events into two, separating events with one b-tagged jet (1-tag) from events with two or more b-tagged jets (2-tag). Events are required to have at least four and at most six jets with transverse energy $E_T > 15$ GeV and $|\eta| < 2.0$. To avoid overlap with other CDF top-quark mass measurements, we reject events with reconstructed electrons or muons with $p_T > 20$ GeV/c and $|\eta| < 1.0$ (lepton + jets final state), and events with $\not\!\!E_T$ significance below 3 GeV$^{1/2}$ (all-hadronic final state), where the $\not\!\!E_T$ significance is defined as $\not\!\!E_T{}^{sig} = \not\!\!E_T/\sqrt{\sum_{jets} E_T}$. For further rejection of multijet backgrounds from QCD processes, we require $\Delta\phi_{min}(\not\!\!E_T, jet) > 0.4$, where $\Delta\phi_{min}(\not\!\!E_T, jet)$ is the smallest separation in the angle ϕ between jets and $\not\!\!E_T$ [14].

Background events with b-tags arise from QCD multijet and electroweak production of W bosons associated with heavy flavor jets. In order to improve the ratio of $t\bar{t}$ signal in the semileptonic channel to the background of this analysis, an artificial neural network is trained to identify the kinematic and topological charateristics of SM $t\bar{t}$ events using eight input variables [14]. We apply the neural network to all events passing the above selections, and make a cut on neural network score that retains 81% of the $t\bar{t}$ signal events while rejecting 91% of background events. The selection criteria listed above define the 'signal region'. We follow Ref. [14] and estimate the background rate using a data-driven method. The method uses events with exactly three jets and employs a per-jet parameterization of the b-tagging probability. Due to the presence of $t\bar{t}$ events in samples with higher jet multiplicity, we extrapolate the b-tagging probability of the three-jet event sample to higher jet multiplicity events by iteratively removing the $t\bar{t}$ content from the sample [14]. We estimate the background for the 1-tag and 2-tag samples separately. A b-tagging correction factor [19] is applied to take into account the fact that most of the heavy flavor jets are produced in pairs. With this procedure we obtain the estimated number of background events in the signal region shown in Table I. We also show the estimated number of $t\bar{t}$ signal events, assuming a $t\bar{t}$ production cross-section of 7.5 pb at $M_{top} = 172.5$ GeV/c^2 [20], together with the number of observed events in the data.

Monte Carlo (MC)-simulated $t\bar{t}$ samples are generated by PYTHIA [21] of 76 different M_{top} values ranging from 150 GeV/c^2 to 240 GeV/c^2, with increments from 0.5 i GeV/c^2n the region immediately above and below 172.5 t GeV/c^2o 5 n GeV/c^2ear the extreme mass regions. For each of them we reconstruct the events with different values of Δ_{JES}, the difference between the jet energy

TABLE I: Number of expected signal and background events and observed data events with integrated luminosity of 5.7 fb^{-1} in the signal region. The $t\bar{t}$ signal contribution is estimated with a cross-section of 7.5 pb, and the background events are dominant with processes of QCD multijet and electroweak production of W bosons associated with heavy flavor quarks. All selection requirements are applied, and events are separated into 1-tag and 2-tag categories.

Events	1-tag	2-tag
Expected $t\bar{t}$ Signal	644.3 ± 118.7	262.9 ± 50.3
Expected Background	410.6 ± 31.7	43.8 ± 11.0
Total Expectation	1054.9 ± 122.9	306.7 ± 51.5
Observed Data	1147	285

scale (JES) in the MC simulation and the data. A total of 27 different Δ_{JES} values, ranging from -3.0 σ_c to +3.0 σ_c, where σ_c is the uncertainty on the JES [22], are used to reduce the systematic effects due to the jet energy uncertainty, as described later.

For each MC-simulated sample in this analysis, we reconstruct three variables using the leading four or five jets to form the templates. The first variable, m_{jj}, defined as the invariant mass of the two jets from the hadronically decaying W boson, serves as an *in situ* constraint of the JES through the likelihood fit described later. We calculate m_{jj} from the two non-b-tagged jets whose invariant mass produces the closest value to the world average W boson mass of 80.40 GeV/c^2 [23]. We also reconstruct the top-quark mass ($m_t^{\rm had,reco}$) from the invariant mass of the three jets whose momentum sum yields the largest p_T since the invariant mass constructed this way has a large correlation with the hadronically decaying top-quark mass. To enhance the probability that the jets used to compute $m_t^{\rm had,reco}$ come from the hadronically decaying top quark, we add two constraints to the calculation of $m_t^{\rm had,reco}$: first, $m_t^{\rm had,reco}$ must contain the two jets that form m_{jj}, and second, in 2-tag events the third jet of $m_t^{\rm had,reco}$ must be b-tagged. A third variable, $m_t^{\rm had,reco(2)}$, is defined as the invariant mass of three jets, two of which are the pair which defines m_{jj}. The third jet of $m_t^{\rm had,reco(2)}$ is required to be the most energetic jet of those not forming $m_t^{\rm had,reco}$, and is also required to be b-tagged in a 2-tag event. The variable $m_t^{\rm had,reco(2)}$ plays as an complementary role to $m_t^{\rm had,reco}$ in extracting information on the top-quark mass, and is particularly important in events where the three jets used to compute $m_t^{\rm had,reco}$ were not the actual decay products of the hadronically-decaying top quark.

The template method used in the extraction of $M_{\rm top}$ requires that a probability density function (p.d.f.) be built for each template. For each MC signal and background sample, we estimate the p.d.f.s using the kernel density estimation (KDE)[24, 25] that employs a non-parametric method to construct p.d.f.s. For each sample, we build a three dimensional p.d.f. from the reconstructed observables (m_{jj}, $m_t^{\rm had,reco}$, and $m_t^{\rm had,reco(2)}$), taking their correlations into account. To measure $M_{\rm top}$, we fit the signal and background p.d.f.s to the distributions of the observables in the data using an unbinned maximum likelihood fit [26] where we minimize the negative logarithm of the likelihood using MINUIT [27]. The likelihood fits $M_{\rm top}$ and Δ_{JES} simultaneously, and is built separately for each subsample, 1-tag and 2-tag events, in order to improve the usage of statistical information. References [25, 28] provide detailed information about this technique.

The mass fitting procedure is tested with pseudoexperiments for a set of MC $t\bar{t}$ samples with 14 different $M_{\rm top}$ values ranging from 159 GeV/c^2 to 185 GeV/c^2. For each pseudoexperiment we select the number of background events from a Poisson distribution with a mean equal to the expected total number of background events in the sample and the number of signal events from a Poisson distribution with a mean equal to the expected number of signal events normalized to a $t\bar{t}$ production cross section of 7.5 pb [20]. The distributions of the average mass residual (the deviation from the input top-quark mass) and the width of the pull (the ratio of the residual to the uncertainty) for simulated experiments are corrected to be zero and unity, respectively. The correction is $M_t^{corr} = 1.24 \times M_t^{meas} - 40.6$ GeV/c^2, where M_t^{meas} is the raw value from the likelihood fit and M_t^{corr} is the corrected value of the measurement. The measured uncertainty is correspondingly increased by 20% to correct the width of the pull distribution.

We examine various sources of systematic uncertainties that could affect the measurement by comparing the results of pseudoexperiments in which we vary relevant parameters within their uncertainties. One of the dominant sources of systematic uncertainty is the residual JES [6, 22]. We vary the JES components within their uncertainties in the generated signal MC events and interpret the shifts in the returned top-quark mass as uncertainties. The b jet energy scale systematic uncertainty that arises from the modeling of b fragmentation, b hadron branching fractions, and calorimeter response captures the additional uncertainty not taken into account in the light quark jet energy scale [6]. The uncertainty arising from the choice of MC generator is estimated by comparing results from MC simulated samples generated with PYTHIA and HERWIG [29]. We estimate the systematic uncertainty due to imperfect modeling of initial-state gluon radiation (ISR) and final-state gluon radiation (FSR) by varying the amounts of ISR and FSR in simulated events [30]. We estimate the systematic uncertainty due to parton distribution functions (PDF's) of the proton by varying the independent eigenvectors of the CTEQ6M [31] PDF's, varying Λ_{QCD} (228 MeV vs. 300 MeV), and comparing CTEQ5M [32] with MRST72 [33] PDF's. To estimate the systematic uncertainty asso-

TABLE II: Systematic uncertainties on M_{top}.

Systematic Sources	Uncertainty (GeV/c^2)
Residual JES	0.5
b-JES	0.3
MC Generator	0.7
Radiation	0.2
PDFs	0.2
gg fraction	< 0.1
Background	0.1
Trigger Modeling	0.1
Multiple Hadron Interaction	0.2
Color Reconnection	0.2
Total Systematic Uncertainty	1.0

ciated with uncertainties in the top-quark production mechanism, we vary the fraction of the top quarks produced by gluon-gluon annihilation from the default 6% to 20%, corresponding to a one standard deviation upper bound on the gluon fusion fraction [34]. We also evaluate the uncertainty due to background modeling effects by re-weighting the background shape up and down and comparing the resulting measurements. We apply an additional uncertainty to account for the effect of the trigger simulation in the signal MC samples, in a similar way to the background shape systematic uncertainty estimation. We also estimate an uncertainty due to the effect of multiple hadron interactions, which takes into account the increasing instantaneous luminosity in this dataset. The color reconnection (CR) systematic uncertainty [35] is evaluated using MC samples generated with and without CR effects adopting different tunes [36] of PYTHIA. Table II summarizes the individual systematic uncertainties considered, giving a total systematic uncertainty of 1.0 GeV/c^2 for the measurement of M_{top}.

By applying a likelihood fit to the data using the three observables described above and the corrections obtained from the simulated experiments, the top-quark mass is measured to be

$$\begin{aligned} M_{top} &= 172.3 \pm 2.4(stat) \pm 1.0(syst)\ \mathrm{GeV}/c^2 \\ &= 172.3 \pm 2.6\ \mathrm{GeV}/c^2. \end{aligned} \quad (1)$$

Figure 1 shows the distribution of the observables used for the M_{top} measurement overlaid with their probability density functions from $t\bar{t}$ signal events with $M_{top} = 172.5$ GeV/c^2 and the estimated background.

In conclusion, we have performed a measurement of the top-quark mass in events with large $\not\!\!E_T$ and jets, corresponding to an integrated luminosity of 5.7 fb^{-1}. The data sample has been chosen in such a way as to exclude events used in other CDF top-quark mass measurements. The result, $M_{top} = 172.3 \pm 2.6$ GeV/c^2, is approximately a factor of 6 improvement from the previous measurement in this channel [9], and is in agreement with other measurements which contribute to the world average of $M_{top} = 173.2 \pm 0.9$ GeV/c^2 [37].

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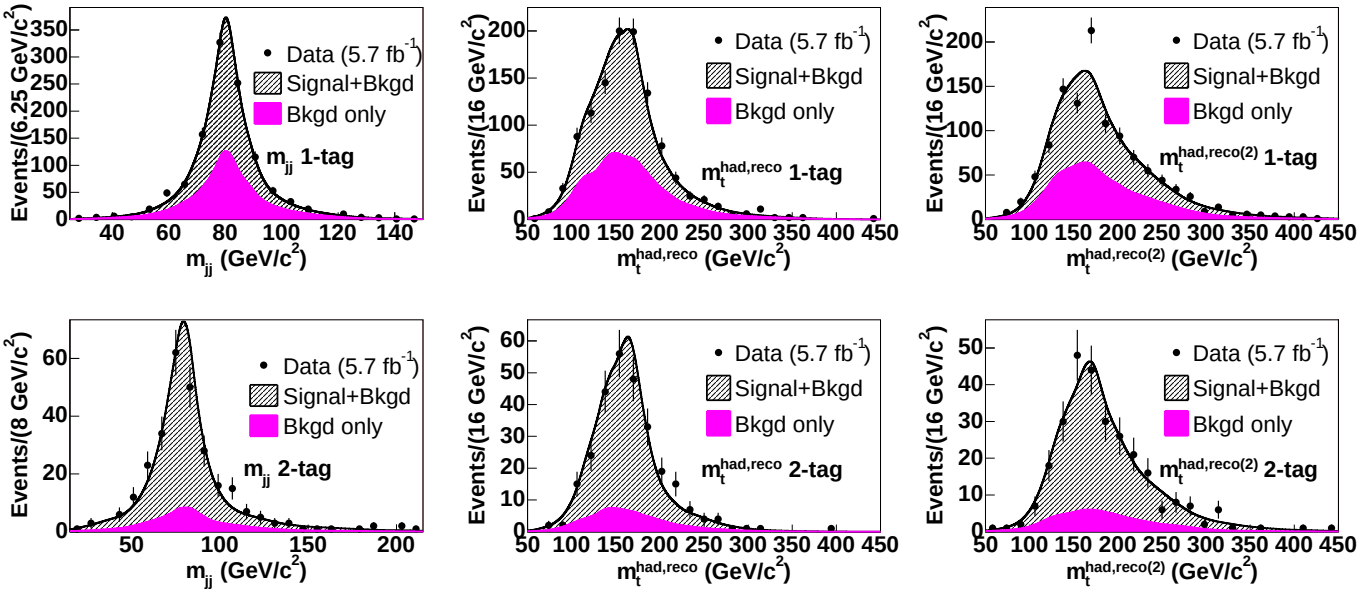

FIG. 1: Distribution of kinematic variables m_{jj}, $m_t^{\rm had,reco}$, and $m_t^{\rm had,reco(2)}$ from data (points), overlaid with their corresponding one dimentional p.d.f.s from signal MC sample ($M_{\rm top} = 172.5$ GeV/c^2, hashed area) plus the estimated background (filled area). Both 1-tag (top) and 2-tag (bottom) events are displayed.

[1] ALEPH, CDF, D0, DELPHI, L3, OPAL, SLD, the LEP Electroweak Working Group, the Tevatron Electroweak Working Group, and the SLD Electroweak and Heavy Flavor Working Groups, arXiv:1012.2367v2.

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